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Quasi-static and high strain rates compressive response of iron and Invar matrix syntactic foams

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ABSTRACT

The present work is focused on developing iron and FeNi36 Invar matrix syntactic foams and studying their properties under quasi-static and high strain rate compression. The quasi-static compression is conducted at a strain rate of 10^{-3} s^{-1}. High strain rate testing is performed using a split-Hopkinson pressure bar (SHPB) at strain rates up to 2500 s^{-1}. One of the limitations of the SHPB method is that it does not provide useful results at the intermediate strain rates where the specimens do not fail completely during the test. In the present study, a recently developed repeated testing scheme is applied to obtain results at such intermediate strain rates. Syntactic foams containing 5 and 10 wt.% hollow glass microballoons (GMBs) are synthesized using the metal powder injection molding (MIM) process for this study. The results show that the yield strength decreases with increasing GMB content. The quasi-static yield strengths of 5 and 10 wt.% GMB syntactic iron foams were found to be 14% and 17% lower than that of iron. Similarly, 5 and 10 wt.% GMB syntactic Invar foams had 35% and 51% lower yield strength than Invar alloy. However, weight-related strength was found to increase with GMB content and exceed the respective data of other iron and steel foams. High strain rate testing revealed a weak trend towards yield strength increase with strain rate. However, the indication of strain rate sensitivity is not very strong due to scatter in data. Metallographic analyses conducted on failed specimens showed that the extent of matrix plastic deformation decreased with increasing strain rate. Particle crushing was observed at all strain rates.

1. Introduction

The high density of iron is one of the limitations that are motivating the efforts of weight reduction in several applications, specifically in automobiles, ships, and infrastructure. The approach of developing lightweight iron based composites and foams is a viable solution for weight reduction. A specific class of lightweight composites is called syntactic foams [1]. Syntactic foams are composites where hollow particles are dispersed in a matrix to create a porous microstructure [2,3]. Aluminum [4–6], magnesium [7–9], and titanium [10–12] matrix syntactic foams have been extensively studied. Engineered hollow spheres of SiC and Al_2O_3 [13–15] and inexpensive fly ash cenospheres [6,7,16] have been used as fillers in these syntactic foams. In comparison with conventional metal foams containing gas porosity in the matrix, each pore of syntactic foams is reinforced by the stiff shell of the hollow particle. This approach of developing a porous material leads to lightweight composites in which the detrimental effects of porosity on the absolute values of mechanical properties are compensated if the material's microstructure is appropriately designed and the properties of the microspheres themselves are adapted to those of the matrix or host material. This is why several recent studies have focused on understanding the failure behavior of particles using single particle testing methods [17,18], in-situ experimental techniques [14,19] and theoretical modeling [20,21]. Among the findings are the observations that the relative stiffness of the matrix and particle material and the particle wall thickness to diameter ratio play an important role in determining the failure characteristics.

Iron based syntactic foams are less common than, e.g., their aluminum based counterparts because of difficulties linked to higher processing temperatures necessitated by this matrix. Their coverage in the published literature is reflected in Table 1 [22–31].

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The table shows that these materials were mostly tested under fatigue, bending, tensile and compressive loading conditions. For the latter case, both quasi-static and dynamic experiments have been carried out on individual materials of this class. Table 1 also lists the major findings of these studies. While development or optimization of synthesis methods is one of the main focus areas in many of them, the synthesized syntactic foams have been characterized for mechanical properties to develop a detailed understanding on the behavior of these materials.

In contrast to iron and steel, a large body of literature is available on aluminum and magnesium matrix syntactic foams due to the relative ease of fabricating them [8,14,32–35]. Stir mixing and pressure infiltration are the two most widely used methods for synthesizing such syntactic foams. In comparison to light metals, the very high melting point of iron makes it challenging to develop synthesis methods for iron and iron alloy matrix syntactic foams. Iron based syntactic foams have been synthesized by mechanical pressure infiltration [23] and melt infiltration [24] and tested under quasi-static compression. Increase in carbon content within these foams was found to enhance the compressive strength and energy absorption capability [23]. These foams were shown to possess an energy absorption capacity per unit mass 6 times and per unit volume 70 times that of aluminum foams [24]. Such superior performance makes iron matrix syntactic foams attractive for the automotive industry and military as well as civil defense structures.

Hollow glass microballoons (GMBs) have been widely used in fabricating polymer matrix syntactic foams [36], their use in iron matrix syntactic foams has only been considered recently. The main limitation in this respect is the high melting point of iron, at which temperature the glass particles lose their strength and stiffness. Pressure or vacuum infiltration methods can thus not

Table 1
Literature survey on iron or steel matrix syntactic foams.

Reference	Syntactic foam	Mechanical Testing	Results
Neville and Rabiei [22]	Matrix: low carbon steel or stainless steel Particles: 3.7 mm and 1.4 mm low carbon steel or 2 mm stainless steel spheres	Quasi-static compression	(1) Energy absorption at densification was higher for stainless steel compared to carbon steel syntactic foam (2) Maximum energy absorption at densification was 68 MJ/m^3 for stainless steel syntactic foam
Castro and Nutt [23]	Matrix: steel Particles: steel or alumina	Compression at 8×10^{-4} s^{-1}	(1) Low carbon and medium carbon syntactic steel foams have energy absorption capacities of 69.45 and 122.68 MJ/m^3, respectively (2) Increase in carbon content of steel foam increased the yield strength
Castro and Nutt [24]	Matrix: steel Particles: steel or alumina	Compression at 8×10^{-4} s^{-1}	(1) The maximum energy absorption at densification was 104.78 MJ/m^3 (2) Increase in relative density of steel foam increases compressive strength and decreases plateau stress (3) Energy absorption capacity increased by six times per unit mass and 70 times per unit volume when compared to Al foams
Peroni et al. [25,26]	Matrix: 99.7% pure iron Particles[*]: S60HS (*d* 30 μm) or iM30 K (*d* 18 μm) glass hollow particles in 5, 10 and 13 wt.%	Compression (1) Quasi-static (10^{-2} s^{-1}) (2) Low (10–20 s^{-1}) (3) High (1000–2000 s^{-1})	(1) Yield strength increased with strain rate and was 47% higher compared to that at quasi-static strain rate (2) Increase in glass microspheres content reduced the material strength (3) Variation of glass microsphere type caused variation in strength and fracture behavior of the material
Weise et al. [28]	Matrix: FeNi36 Particles: S60HS (*d* 30 μm) glass hollow particles at 5 wt.%	Tension	(1) Focus on production process: Comparison of different powders, use of fine powders was beneficial (2) 60% Reduction in ultimate tensile strength at 30% density reduction (3) Limited amount of ductility retained even with GMB additions under tensile load
Weise et al. [54]	Matrix: 316L Particles: S60HS (*d* 30 μm) glass hollow particles at 5.3 and 10 vol.%	Compression, tension	(1) High sintering temperatures lead to disintegration of glass microspheres, porosity retained, but glass phase embedded within the metal phase rather than supporting pores as in a true syntactic foam (2) Property scaling of QS compressive strength according to a power law with exponent 1.13, in between typical values for syntactic and non-syntactic closed-cell foams
Peroni et al. [31]	Matrix: 316L Particles: S60HS (*d* 30 μm) glass hollow particles at 40 and 60 vol.% and Fillite 106 cenospheres at 40 vol.%	Compression (1) Quasi-static (10^{-2} s^{-1}) (2) Low (10–20 s^{-1}) (3) High (1000–2000 s^{-1})	(1) Cenospheres remain intact and yield a high quality syntactic foam. (2) Strength loss with decreasing density less significant for cenosphere-compared to glass microsphere-based materials (3) Strain-rate based strength increases by 25% for both glass and cenosphere-based variants
Brown et al. [29]	Matrix: low carbon steel or stainless steel Particles: low carbon steel or stainless steel	Three-point bending	(1) Flexural yield strength of 40 MPa, which is close to the compressive yield strength (42 MPa) (2) Plateau strength under compression was 50% higher than ultimate bending strength (3) Ductile failure due to the propagation of preexisting microporosity in the matrix
Vendra et al. [30]	Matrix: low carbon steel or stainless steel Particles: low carbon steel or stainless steel	Compression–compression fatigue	(1) At a maximum fatigue load of 50% to that of plateau strength and 1 million cycles, stainless steel syntactic foam showed a total strain of 8% (2) Superior fatigue properties due to strong bonding between the hollow spheres and matrix

[*] *d* Refers to the diameter of the particle.